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Anthropogenic and Natural Stresses on Selected Coral Reefs in Hawai'i: A Multidecade Synthesis of Impact and Recovery[1]

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Abstract: In 2002, quantitative phototransect surveys documenting coral community structure off three coastal resorts in Hawai'i were repeated to produce long-term data sets of 12 to 22 yr duration. At the first site, in Honolua Bay off the Kapalua Resort on Maui, a runoff event from surrounding pineapple fields following a winter storm in early 2002 deposited sediment on the inner reef that remained in the bay for at least 6 months. Between 1992 and 2002 survey data showed that significant declines in coral cover occurred on seven of eight transects, causing an overall reduction in coral cover of about 33% throughout the entire bay. Rainfall records indicate that the 2002 storm was of relatively small magnitude; however subsequent resuspension and flushing by waves did not take place for several months, exacerbating the smothering effects of the sediment. Periodic sedimentation events of various magnitude and duration have resulted in cycles of damage and recovery that have produced a coral community that reflects intermediate disturbance and a coral community structure dominated by sediment-resistant species. The two other long-term surveys, off Mauna Lani Resort on the west coast of the island of Hawai'i (1983–2002), and Princeville Resort on the north shore of Kaua'i (1980–2002), both revealed a pattern of consistent increase in coral cover at all stations. At these open coastal sites, anthropogenic effects are undetectable relative to natural factors that affect coral community structure. A lack of maximum wave events during the interval between surveys may partially explain the increase in coral cover. Activities from shoreline development appeared to have no effect on coral community structure during the study interval. The results of these three studies suggest a framework for coral reef management in Hawai'i by concentrating efforts on embayments and areas with restricted circulation. Because such areas compose less than 10% of the coastal areas, the overall condition of the majority of coral reefs in Hawai'i is relatively good. Nevertheless, embayments are major recreational sites and it is these environments for which we suggest that the major need for management exists and should be focused. On a global scale, concerns of catastrophic loss from anthropogenic impact to coral reefs may be valid in many areas of the world, but they do not accurately depict the condition of coral reefs in Hawai'i.

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In recent years, coral reef ecosystems worldwide have experienced increasing stress associated with increases in human population and economic growth (Ginsburg 1993, Bryant et al. 1998, Wilkinson 2000). This is particularly true in Southeast Asia and the Caribbean Basin, where anthropogenic stress often exceeds impacts caused by natural disturbance. In Hawai‘i, and the Pacific oceanic islands in general, anthropogenic impacts exist, but the magnitude and extent of alteration of the ecosystems is not as extreme as in other oceans (Grigg 1997, Grigg and Birkeland 1997, Maragos 1997, Bryant et al. 1998). Nevertheless, Pacific island coral reefs are often included with other reef areas experiencing much more severe degradation and have been described as ecosystems in crisis (Hodgson and Liebeler 2002). In fact, in Hawai‘i, there is a strong perception that a variety of anthropogenic activities are seriously altering the structure and function of coral reefs. In part, this view has come about owing to the lack of long-term studies on coral reefs and the difficulty in distinguishing impacts caused by natural vis-à-vis human-induced factors. This remains a difficult but important objective in coral reef science.

Coral communities are normally long-lived, slow-growing, but ever-changing assemblages that often require many decades to reach successional maturity (Grigg and Maragos 1974, Pearson 1981). Coral communities are also notably patchy in their pattern of distribution and abundance in both space and time and are sometimes referred to as spatio-temporal mosaics (Grassle 1973, Bak and Luckhurst 1980, Done 1992). Changes in their community structure may be subtle, due to long-term but chronic low-grade stress (e.g., turbidity), or catastrophic, in the case of large-scale episodic events (e.g., hurricane waves), which may have return periods of several to many decades (Dollar 1982, Dollar and Tribble 1993). Long-term studies based on survey time-series show that benthic assemblages are useful indicators of environmental impact. Because corals are long-lived sessile organisms and are exposed to conditions in the water column, they must either tolerate and adapt to the environment or die.

These are reasons why long-term data sets or time-series are necessary to understand the population and community dynamics of coral reef communities. Unfortunately, scientific studies are rarely funded for more than several years, explaining why few long-term (decadal) data sets exist in Hawai‘i or elsewhere. However, over the course of the last several decades, we have been able to revisit seven coral reef sites in the Hawaiian Islands that share commonalities in terms of their exposure to both natural and human-induced stress. Knowing the general history of both natural and anthropogenic change at these sites, we have been able to correlate both natural and anthropogenic stress to changes in coral community structure. In 2001, a National Oceanic and Atmospheric Administration grant provided a further opportunity to revisit all seven sites, thus extending the length of investigation up to three decades. Although these data sets represent relatively long histories, they all suffer from hindsight. Had the length of the studies been originally planned, revisits would have been more systematic and frequent. Hence, the data have some statistical limitations, in terms of establishing cause and effect. Nevertheless, these data sets provide a unique opportunity to identify long-term patterns of change within coral communities that can be correlated with both anthropogenic factors and natural forcing.

In this paper, the results for three of the study sites are reported: Honolua Bay on Maui, the reef in front of the Mauna Lani Resort on the Kona coast of the island of Hawai‘i, and the reef offshore of the Princeville Resort on Kaua‘i (Figures 1 and 2). All three sites are adjacent to large resort complexes that include golf courses that extend to the coastline. The site on Maui is also surrounded by large-scale agriculture of pineapple.

The investigative approach was to revisit each site and conduct a final survey of coral community structure to extend the length of the time-series. Changes in coral community structure were correlated with site-specific histories of both natural and anthropogenic sources of stress unique to each site. In this way, we were able to distinguish anthro-

FIGURE 1. Aerial photograph of Honolua Bay, West Maui, showing locations of four transect stations (eight transects) that were surveyed in 1990, 1992, and 2002. Honolua Stream enters the bay at lower left corner at widest point of the beach. Note pineapple fields adjacent to bay on right. Inset map shows locations of three resort sites that were studied.

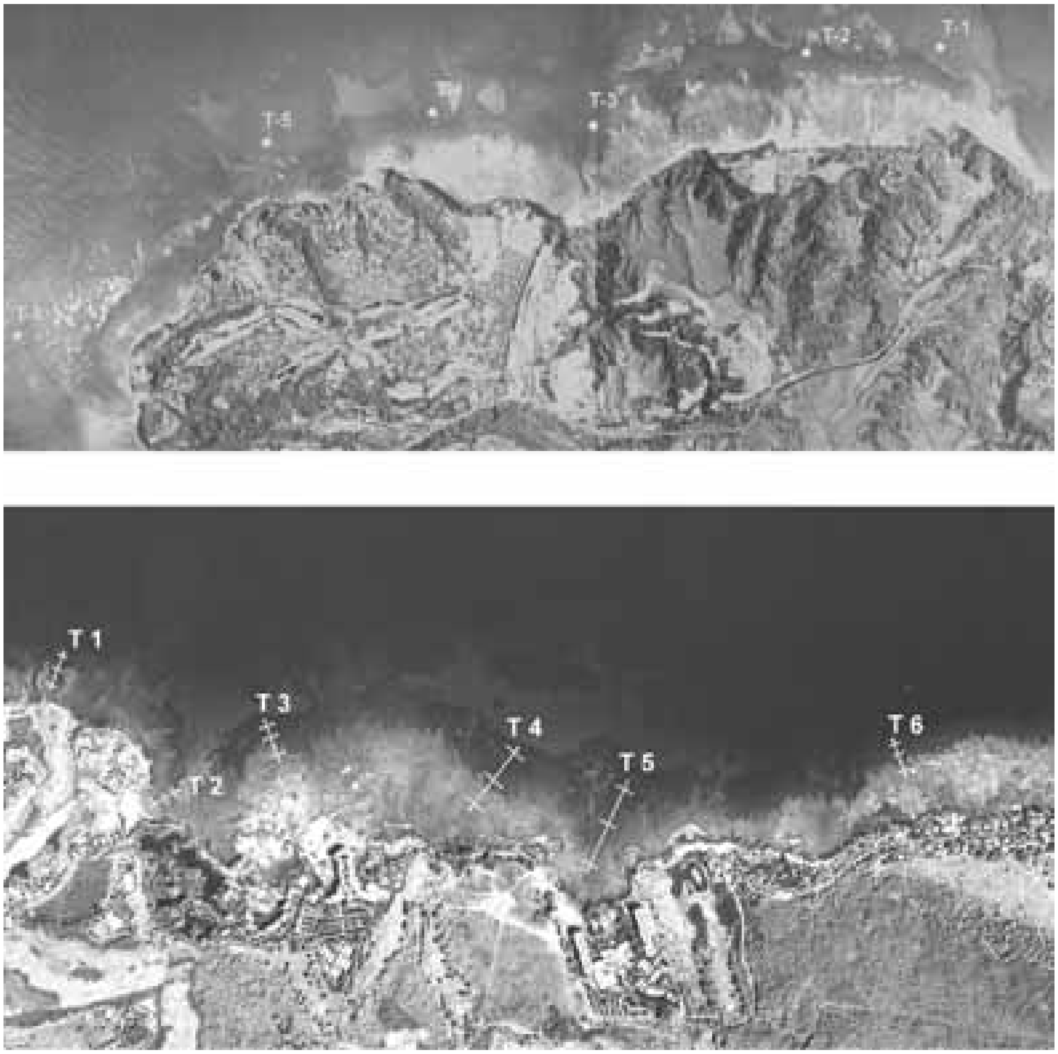

Figure 2. Aerial photographs of Mauna Lani Resort on the coastline of West Hawai'i (*top*), and Princeville Resort on the north shore of Kaua'i (*bottom*). Also shown are locations of repeated coral transect survey stations.

pogenic from natural forcing and accordingly generate recommendations for coral reef management. Understanding the impacts of resort development on coral reefs is important, not only as an environmental issue but also for economic considerations. The visitor industry in Hawai'i is a leading factor in the economy of the state, generating at least $10 billion annually for the last decade (Department of Business, Economic Development, and Tourism 2000). Understanding the impact of anthropogenic activities is imperative before effective management strategies can be developed and implemented.

MATERIALS AND METHODS

A photoquadrat transecting method, modified after Kinzie and Snider (1978), was utilized to analyze coral community structure. At each survey site, a transect tape 50 m long was paid out along the bottom at a constant depth.

Transects were located at representative locations, but data were collected at random points along the transect line. A rectangular quadrat frame with dimensions of 1 by 0.66 m was sequentially placed over 10 random marks on the tape, where a color photograph was taken recording each segment of reef area enclosed by the quadrat frame. In addition to the photoquadrats, divers familiar with Hawaiian taxonomy of resident species (S. Dollar, R. Grigg) visually estimated the percentage cover of each coral species, algae, and barren substrata (i.e., sand, limestone, rubble) enclosed within each quadrat frame.

In the laboratory, area coverage of each component of bottom cover in the quadrat photographs was determined using an overlay grid divided into 100 equally sized segments. The number of segments of each benthic species and substratum type was summed to calculate area coverage. Species identification and area coverage in the photographs was verified using the field notes. This method gives accurate estimates of abundance of both common and rare (inconspicuous) organisms. Because virtually 100% of the coverage of each quadrat becomes part of the data record, no information is lost.

Results of the photoquadrats and in situ cover estimates were used to calculate indices of community structure, abundance and distribution (e.g., percentage cover, number of species), and species cover diversity ($H'c$) (Pielou 1966). Because each quadrat is a replicate, each transect contains 10 samples. The nonparametric Wilcoxon matched-pairs signed-rank test was used to test for significance between transects in both space and time (Siegal 1956).

In Honolua Bay, four pairs of transects were conducted: two pairs on each side of the reef platform separated by the submerged paleostream channel (Figure 1). At Mauna Lani, five sets of transects were located along the length of the resort property. Each set included three transects, one in each major coral zone described in Dollar (1982) at depths of approximately 6, 10, and 20 m (Figure 2). At Princeville, six survey sites at a depth of about 12 m on the submarine terrace were evenly spaced along 8 km of coastline fronting Princeville from Hanalei Bay to Kalihiwai (Figure 2). Only one depth zone was surveyed at each site off Princeville because it represented optimal habitat.

Nutrient concentrations (nitrate + nitrite, orthosphosphate, ammonium, silica, total nitrogen, total phosphorus) were also measured at all transect sites within the three study areas. However, these results are reported elsewhere because in no case were nutrient concentrations found to be correlated with changes in coral reef community structure.

RESULTS

Honolua Bay

Honolua Bay is located on the northwestern tip of the island of Maui (Figure 1). The bay, along with adjacent Mokulē'ia Bay, was designated as a Marine Life Conservation District (MLCD) in 1978. Honolua Stream flows into the most landward end of the bay, and as a result, there is a submerged paleostream channel through the center of the bay. On both sides of the bay, reef platforms extend from the shoreline. The reef platforms terminate in steeply sloping edges that extend to a sandy submerged stream channel.

Of the 140 ha (1.4 km^2) composing the developed watershed above Honolua Bay, approximately 110 (1.1 km^2) have been cultivated in pineapple since 1953. Before pineapple, the land consisted of pasture grazed by cattle. The remaining 30 ha currently consists of the Kapalua Resort (opened in 1976), which is comprised of three golf courses, three hotels, and substantial residential uses. Because of problems with storm runoff affecting the popular recreational area of Honolua Bay, the Maui Pineapple Company, with support from federal funding, completed 22 "Best Management Practices" in the Honolua watershed between 1994 and 1996. These "BMPs" included the construction of diversion ditches, terraces, filters, and siltation basins (Maui Pineapple Co. 1999).

In 1990, Kapalua Land Co. initiated a marine biological and water quality monitoring program in Honolua Bay in response to concerns that the bay was experiencing negative impacts owing to shoreline development. In

1992 a second assessment of the coral community structure in the bay was conducted. In July 2002, the coral community in the bay was again assessed, providing a 12-yr span between surveys (1990–2002). Honolua Bay was also a site in a study in which reef community structure within MLCDs was compared with an unprotected control area (Grigg 1994).

In 1990, from 6 to 12 species occurred on transects, with mean coral cover ranging from 38 ± 6% (SE) to 89 ± 5% (Table 1). In

TABLE 1

Percentage Cover, Species Number, and Species Cover Diversity (*H′c*) for Phototransects Conducted in 1990, 1993, and 2002 in Honolua Bay, Maui, Hawai'i

	Transect											
	I-1			I-2			II-1			II-2		
Species	1990	1992	2002	1990	1992	2002	1990	1992	2002	1990	1992	2002
Porites lobata	7.2	10.4	18.6	10.6	18.9	8.8	9.0	15.7	21.8	22.2	20.4	13.1
Porites compressa	4.2	3.5	1.9	12.2	8.8	4.6	2.3	8.9	6.3	46.3	44.7	29.0
Porites brighami	0.3						0.1					
Pocillopora meandrina			2.1		0.8	1.2	0.2	1.6	4.3			2.1
Pocillopora eydouxi	0.7			0.7			1.7					
Montipora dilatata	5.9	21.1	3.4	32.9	34.8	6.4	4.0	12.8	5.0	11.8	22.4	11.6
Montipora patula	4.9	18.6	2.2	12.9	6.9	2.4	7.5	18.9	5.1	4.6	1.1	4.0
Montipora flabellata	13.7	18.5	20.9	7.8			11.9	14.1	1.3			
Pavona varians	1.2	0.8	0.2	0.6	1.0		1.8	3.0	0.3	3.7	0.1	0.4
Pavona duerdeni		1.6	0.1				1.0	0.3				
Leptastrea purpurea							0.1		0.1			
Palythoa tuberculosa					0.1			0.2		0.1		
Cyphastrea ocellina	0.3				0.1		0.1					
Transect total	38.4	74.5	49.4	77.7	71.4	23.4	39.7	75.5	44.2	88.7	88.7	60.2
SE	6.1	5.0	4.6	6.5	6.7	4.2	5.6	4.2	3.7	5.1	3.5	8.3
Species number	9	7	8	7	8	5	12	9	8	6	5	6
Species diversity	1.73	1.60	1.35	1.53	1.31	1.43	1.85	1.79	1.50	1.25	1.08	1.33

	Transect											
	III-1			III-2			IV-1			IV-2		
Species	1990	1992	2002	1990	1992	2002	1990	1992	2002	1990	1992	2002
Porites lobata	27.6	50.6	8.0	14.0	0.1	19.3	35.1	27.7	34.7	28.8	2.5	0.7
Porites compressa	11.1	7.2	1.7	24.5	59.9	25.7	3.2	33.6	0.2	17.7	49.1	40.8
Pocillopora meandrina		3.0	1.5				0.3	0.4	2.4	1.3		
Pocillopora eydouxi							7.6			0.0		
Montipora dilatata	18.5	4.8	3.8	37.0	7.3	10.6	3.8	1.7	0.6	24.5	17.4	0.8
Montipora patula	15.7	11.5	2.3	14.4	6.0	4.8	5.4	5.7	3.1	12.1		4.5
Montipora flabellata		1.8	1.7		0.1		5.2		0.6	0.5		
Pavona varians	2.8	0.2		0.9	1.7	1.2	2.0			1.2	2.4	1.4
Pavona duerdeni	3.1	0.8					0.4				1.3	
Leptastrea purpurea		0.1							0.2	0.2		
Psammocora stellata					5.4							
Cyphastrea ocellina		0.1										
Leptastrea bottae								0.1				
Transect total	78.8	80.1	19.0	90.8	80.5	61.6	63.0	69.2	41.8	86.3	72.7	48.2
SE	6.6	4.5	4.1	2.5	6.2	8.8	4.2	3.7	4.8	4.3	3.2	6.5
Species number	6	10	6	5	7	5	9	6	7	8	5	5
Species diversity	1.55	1.25	1.57	1.34	0.91	1.31	1.48	1.05	0.68	1.49	0.91	0.59

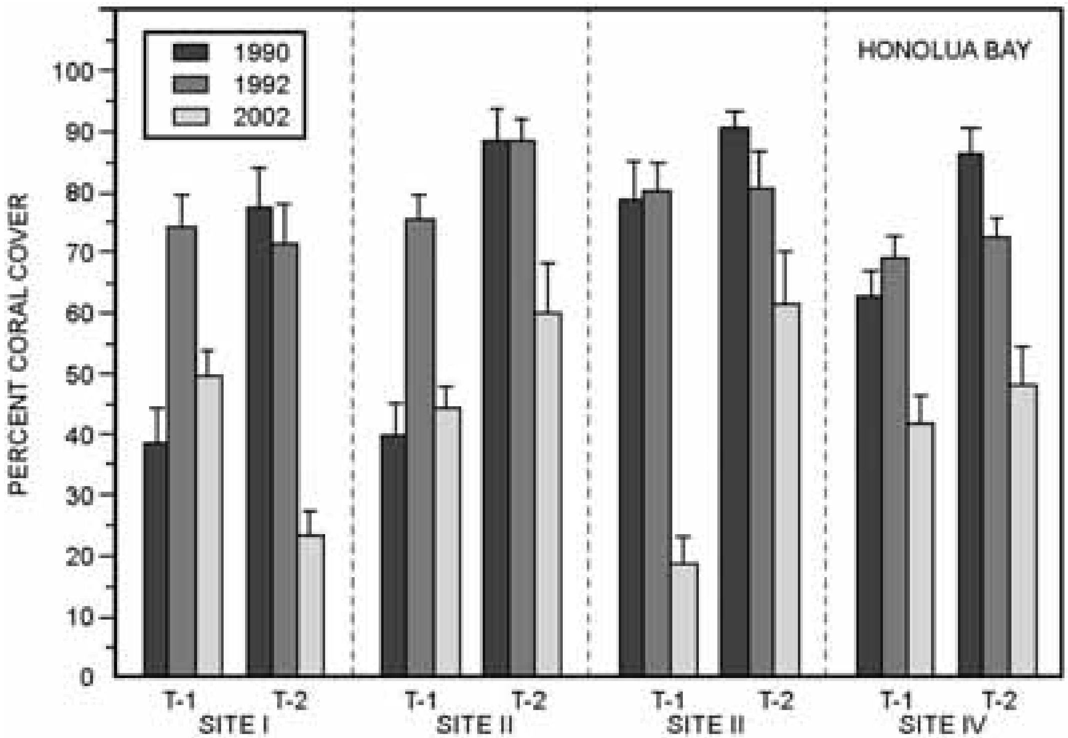

FIGURE 3. Histogram showing total mean coral cover (+SE) from benthic transect surveys in Honolua Bay in 1990, 1992, and 2002.

1992, mean cover ranged from 69 ± 4% to 89 ± 3%. During both of these surveys, coral cover was lower on the shallower reef flats and higher on the deeper reef slopes (Table 1, Figure 3). Although coral cover increased on four transects and decreased on three transects between 1990 and 1992, none of the changes was significant (Wilcoxon matched-pairs signed-ranks test, two-tailed test, $P =$ 0.01) (Table 2). Coral cover diversity ($H'c$) was higher on all transects in 1990 compared with 1992 (Table 1).

A winter storm with high rainfall in January 2002 resulted in substantial input of terrigenous sediment to the bay through stream discharge. Furthermore, erosion of soil from cultivated pineapple fields with subsequent drainage to Honolua Bay has been documented from at least 1964 (Maui Pineapple Co. 1999). Approximately 6 months after the 2002 storm a third survey of coral community structure in the bay was conducted. At the time of the survey (July 2002), deposits of muddy red sediment up to 10 cm thick covered the sand in the inner central channel, as well as some of the reef structure at the location of transect I-2 (Figure 4*A*). No terrigenous sediment remained on the upper reef platforms, although dead coral was abundant (Figure 4*B*,*C*).

A dense growth of benthic algae (*Chrysocystis fragilis* [family Chrysophyta]) also covered much of the outer reef in the vicinity of site IV in July 2002. *Chrysocystis fragilis* is a gelatinous colonial alga that is found on reef flats throughout the Pacific and reproduces primarily by asexual colony fragmentation (Lobban et al. 1995). In Hawai‘i, this alga is often observed during the summer months when wave action is minimal, attached to

TABLE 2

Observed Test Criteria for Nonparametric Wilcoxon Matched-Pairs Signed-Ranks Test for Related Samples Comparing Total Coral Cover on 10 Quadrats Composing Transects at Honolua Bay, Mauna Lani, and Princeville Between Sampling Dates

	Transect								
Honolua Bay	I-1	I-2	II-1	II-2	III-1	III-2	IV-1	IV-2	—
1990–1992	__0**__	23	__1**__	27	25	17	17	8	
1992–2002	4*	0**	0**	4*	0**	15	2**	4*	
1990–2002	15	1**	22	8	0**	0**	10	1**	
Mauna Lani	T-1-6	T-1-10	T-1-20	T-2-6	T-2-10	T-2-20	T-3-6	T-3-10	T-3-20
1993–2002	__0**__	__3**__	__0**__	11	__2**__	28.0	__0**__	__0**__	10
	T-4-6	T-4-10	T-4-20	T-5-6	T-5-10	T-5-20	T-6-6	T-6-10	T-6-20
1993–2002	__0**__	12	26	__0**__	__0**__	13	16	__0**__	__4*__
Princeville	T1	T2	T3	T4	T5	T6	—	—	—
1980–1995	__4*__	__5*__	__7__	8	7	ND			
1995–2002	15	__2**__	__2**__	17	15	ND			
1980–2002	__0**__	__0**__	__1**__	__2**__	__1**__	__0**__			

Note: *, indicates significant difference for two-tailed tests ($P = 0.02$); **, indicates significance for two-tailed test ($P = 0.01$). Underlined test criterion indicates significant decrease in cover; **bold** test criterion indicates significant increase in coral cover between surveys. ND, indicates no data for transect 6 at Princeville in 1995. Individual quadrat data missing for Mauna Lani in 1980. For locations of transects, see Figures 1, 2.

Porites compressa colonies at depths of 15–25 m. The slightest water motion is adequate to dislodge and resuspend the alga from its point of attachment. Usually, *C. fragilis* is removed from the reef during winter months by surge from long-period swells and does not re-establish until calm periods recur in the summer. During the 2002 survey, *C. fragilis* occurred in the densest aggregations ever observed by us on Hawaiian reefs, covering about 26% of the bottom on transect IV-2 (Figure 4*D*). Future observations will be necessary to substantiate if it caused coral mortality.

Mean coral cover in 2002 decreased significantly on seven of the eight transects between 1992 and 2002 and on four of the eight transects between 1990 and 2002 ($P = 0.02$) (Table 2). The greatest decreases in total mean coral cover between 1990 and 2002 occurred at transects I-2 and III-1, located in the inner bay where sediment deposition was the greatest. Coral cover diversity ($H'c$) showed the same pattern as coral cover, with decreases on four of the eight transects between 1992 and 2002 and six of the eight transects between 1990 and 2002 (Table 1).

If coral cover on all transects is pooled, the most abundant species is *Porites lobata* in the 1990 and 2002 surveys and *Porites compressa* in 1992 (Table 3). *Montipora dilatata* ranked second in 1990 and 1992 and third in 2002. *Montipora* is known to be a highly sediment-resistant genus (Te 1998). Hodgson (1989) observed colonies of *Montipora capitata* in Kāneʻohe Bay, Hawaiʻi, that had survived

FIGURE 4. Transect photographs showing sediment remaining on reef in southern part of Honolua Bay (*A* and *B*); sediment-free reef substratum on the north side of Honolua Bay (*C*); *Chrysocystis fragilis* growing on *Porites compressa* in outer Honolua Bay (*D*); *Pocillopora meandrina* zone off Mauna Lani (*E*); *Porites lobata* zone off Mauna Lani (*F*); deep-reef zone with nearly complete coral cover of the bottom off Mauna Lani with transect stake placed on the reef in 1983 (*G*); and encrusting corals typically found off Princeville, Kauaʻi (*H*).

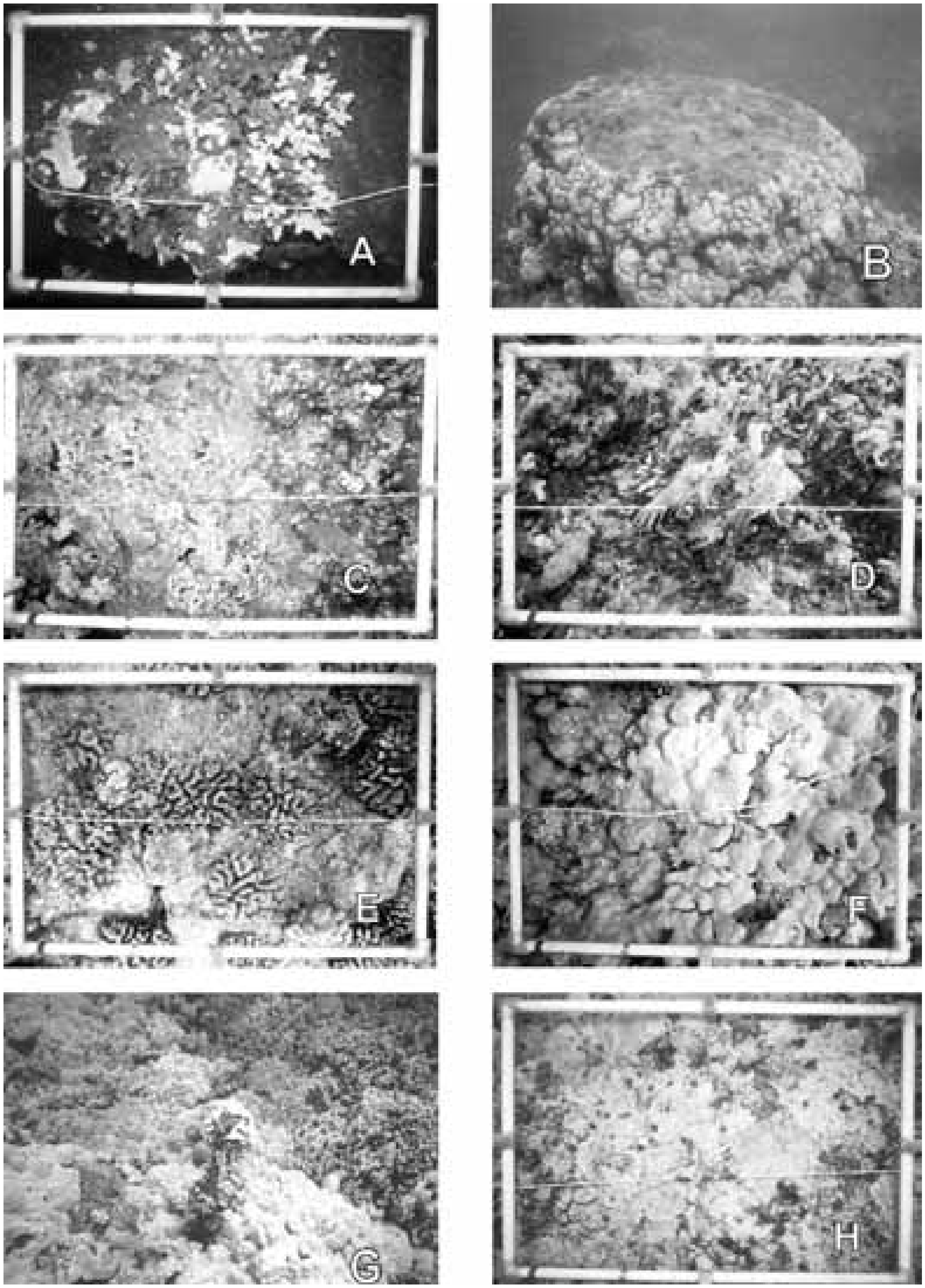
A
B
C
D
E
F
G
H

TABLE 3

Pooled Coral Cover Data for Transects in Honolua Bay, Mauna Lani, and Princeville Showing Relative Percentage of Coral Cover (%cc) and Percentage of Total Bottom Cover (%bc) for Three Surveys

	Honolua Bay					
	1990		1992		2002	
Species	%cc	%bc	%cc	%bc	%cc	%bc
Porites lobata	27.42	19.31	23.87	18.29	35.98	15.63
Montipora capitata	24.57	17.30	25.13	19.25	11.92	5.18
Porites compressa	21.57	15.19	30.03	23.00	31.72	13.78
Montipora patula	13.76	9.69	11.21	8.59	8.18	3.55
Montipora flabellata	6.94	4.89	5.63	4.31	7.05	3.06
Pavona varians	2.52	1.78	1.50	1.15	0.89	0.39
Pocillopora eydouxi	1.90	1.34	0.00	0.00	0.00	0.00
Pavona duerdeni	0.80	0.56	0.60	0.46	0.09	0.04
Pocillopora meandrina	0.32	0.23	0.95	0.73	4.15	1.80
Porites brighami	0.07	0.05	0.00	0.00	0.00	0.00
Cyphastrea ocellina	0.07	0.05	0.07	0.05	0.00	0.00
Leptastrea purpurea	0.05	0.04	0.07	0.05	0.03	0.01
Porites rus	0.00	0.00	0.88	0.68	0.00	0.00
Leptastrea bottae	0.00	0.00	0.02	0.01	0.00	0.00
Palythoa tuberculosa	0.00	0.00	0.05	0.04	0.00	0.00
Total	100.00	70.41	100.00	76.60	100.00	43.43
	Mauna Lani					
	1983		1993		2002	
Species	%cc	%bc	%cc	%bc	%cc	%bc
Porites lobata	68.92	37.20	62.61	30.55	53.92	43.27
Porites compressa	25.83	13.94	32.46	15.84	28.36	22.76
Pocillopora meandrina	3.67	1.98	1.97	0.96	9.55	7.66
Montipora patula	0.65	0.35	1.14	0.56	3.34	2.68
Pavona varians	0.52	0.28	0.43	0.21	1.31	1.05
Montipora capitata	0.32	0.17	1.16	0.57	3.45	2.77
Leptastrea purpurea	0.07	0.04	0.10	0.05	0.02	0.02
Pocillopora eydouxi	0.00	0.00	0.08	0.04	0.06	0.04
Cyphastrea ocellina	0.01	0.01	0.02	0.01	0.00	0.00
Palythoa tuberculosa	0.00	0.00	0.02	0.01	0.00	0.00
Porites brighami	0.00	0.00	0.00	0.00	0.01	0.01
Pavona duerdeni	0.00	0.00	0.01	0.01	0.00	0.00
Total	100.00	53.97	100.00	48.80	100.00	80.25

several weeks of substantial sediment accumulation, apparently without causing tissue damage. He suggested that resistance to sediment stress is a combination of sediment clearing efficiency and biological resistance to infection by microbes in the sediment. *Montipora* spp. are the most abundant corals in the inner portions of Honolua Bay. Clearly, they are the most exposed and resistant species to sedimentation. *Porites compressa*, which is the usually dominant species in similar sheltered embayments, composed only about 30% of total coral cover in Honolua Bay (Table 3).

Mauna Lani

The Mauna Lani Resort is located in the South Kohala District on the west coast of

TABLE 3 (continued)

	Princeville					
	1983		1993		2002	
Species	%cc	%bc	%cc	%bc	%cc	%bc
Porites lobata	40.6	6.9	27.1	6.9	20.4	7.9
Montipora patula	24.9	4.2	32.7	8.3	36.0	13.9
Porites compressa	9.3	1.6	2.4	0.6	4.9	1.9
Montipora flabellata	7.4	1.3	9.6	2.4	14.3	5.5
Montipora capitata	5.7	1.0	9.3	2.4	10.0	3.9
Pocillopora meandrina	4.5	0.8	10.6	2.7	5.5	2.1
Pavona varians	3.4	0.6	1.9	0.5	1.3	0.5
Pavona duerdeni	2.7	0.5	2.9	0.7	3.0	1.2
Porites brighami	0.3	0.1	0.0	0.0	0.0	0.0
Palythoa tuberculosa	1.1	0.2	1.6	0.4	3.8	1.5
Fungia scutaria	0.1	0.0	0.1	0.0	0.0	0.0
Porites (*S.*) *canvexa*	0.0	0.0	0.0	0.0	0.1	0.0
Pocillopora eydouxi	0.0	0.0	0.0	0.0	0.6	0.2
Psammocora stellata	0.0	0.0	1.0	0.3	0.0	0.0
Pocillopora damicornis	0.0	0.0	0.5	0.1	0.0	0.0
Cyphastrea ocellina	0.0	0.0	0.4	0.1	0.0	0.0
Total	100.00	16.94	100.00	25.38	100.00	38.60

Note: Order of species in table is based on highest rank of abundance in earliest survey.

the island of Hawai'i (Figure 1, inset). The resort encompasses approximately 5 km of coastline and currently includes two hotels, two golf courses, and numerous private residences (Figure 2, *top*). Because the Mauna Lani Resort was one of the first major resorts on the South Kohala coast, the reef communities in the area have been subjected to the effects of the resort and associated golf courses for a period of about three decades.

The first marine community assessment was carried out in 1983 and was repeated in 1993 as part of the planning for the construction of an inland marina. It was replicated a third time in August 2002 as part of the current study. During the 1993 and 2002 surveys, a sixth transect site was added off the community of Puakō, to the north of the Mauna Lani property. This site was added to serve as a "reverse control" for possible impacts of sewage disposal. The entire coastal community of Puakō utilizes cesspools and septic systems for domestic waste disposal because there is no municipal sewage system serving the area. After processing within the septic systems and cesspools, domestic sewage leaches to groundwater and eventually enters the coastal ocean. In contrast, at the Mauna Lani Resort all domestic sewage is processed at an on-site treatment plant and the effluent is used for golf course and landscape irrigation.

The western coastline of the island of Hawai'i is not generally exposed to long-period winter swells generated by North Pacific storms, owing to protection from the island of Maui. "Kona" storms from the southwest occasionally impact the area (Dollar 1982) but none occurred between 1993 and 2002. As a result, the West Hawai'i coastline has been relatively free of wave disturbance for the last two decades. In addition, the coastal region of West Hawai'i is one of the driest areas in the state and contains no permanent streams. When intense rainfall events occur, most of the rain percolates through the coastal lava surfaces, with little runoff reaching the ocean.

The Mauna Lani reef tract consists primarily of a narrow, shallow basalt bench that extends from the shoreline to approximately 50–75 m offshore. At the edge of the bench a

TABLE 4

Percentage Cover, Number of Species, and Species Cover Diversity ($H'c$) for Photoquadrat Transects Conducted in 1983, 1993, and 2002 off the Mauna Lani Resort, South Kohala, Hawai'i

	Transect																	
	T-1-6			T-1-10			T-1-20			T-2-6			T-2-10			T-2-20		
Species	1983	1993	2002	1983	1993	2002	1983	1993	2002	1983	1993	2002	1983	1993	2002	1983	1993	2002
Porites lobata	3.1	13.4	56.7	12.5	30.3	42.5	11.3	18.8	34.2	36.0	25.1	36.7	25.3	56.1	63.7	46.5	26.3	52.4
Porites compressa			0.7	2.4	1.6	14.9	37.3	40.7	50.7	14.8	8.8	5.3	0.3	2.9	15.1	38.7	62.3	28.8
Porites brighami									0.1									
Pocillopora meandrina	8.5	3.0	1.6	0.1	0.4	4.6	0.1	0.5	0.2	2.2	2.0	3.5	6.8	2.0	1.3	2.3	0.1	2.2
Pocillopora eydouxi											0.7							
Montipora patula	0.1	0.2	4.8		0.2	4.9		0.8	4.3	4.3	4.5	5.7	0.3	0.7	6.4	0.5	0.7	6.4
Montipora capitata	0.1	0.2	5.6	0.3	2.0	12.4		0.8	0.6	0.6		13.4	0.2	1.2	0.8	0.9	0.4	
Pavona varians	0.1	0.1	0.6	0.1	0.2	0.4		0.2	2.3	3.1	0.4	1.3	0.6		2.9	0.3	0.9	2.9
Pavona duerdeni																		
Leptastrea purpurea	0.1	0.1			0.2	0.3							0.1			0.1		
Cyphastrea ocellina										0.1								
Transect total	12.0	17.0	70.0	15.4	34.9	80.0	48.7	61.8	92.4	61.1	41.5	65.9	33.6	62.9	90.2	89.3	90.7	92.7
SE	3.5	2.8	7.6	4.2	5.9	4.7		9.2	3.2	8.9	7.8	6.3	7.5	5.9	3.5	5.4	4.5	1.9
Species number	6	6	6	5	7	5	3	6	7	6	6	6	7	5	6	7	6	6
Species diversity	0.75	0.66	0.72	0.85	0.56	1.32	0.55	0.81	1.00	1.17	1.14	1.30	0.74	0.48	0.95	0.99	0.73	1.33

	Transect																	
	T-3-6			T-3-10			T-3-20			T-4-6			T-4-10			T-4-20		
Species	1983	1993	2002	1983	1993	2002	1983	1993	2002	1983	1993	2002	1983	1993	2002	1983	1993	2002
Porites lobata	14.1	5.4	39.7	47.1	36.7	43.2	19.7	20.5	31.9	3.5	27.4	37.3	21.2	59.4	67.3	21.1	39.7	35.6
Porites compressa				10.2	0.6	42.1	56.3	55.5	58.8				22.4	12.9	18.3	51.4	50.0	52.1
Porites brighami													0.4					
Pocillopora meandrina	3.1	1.6	26.8	4.2	1.0	0.8		0.3	1.0	1.9	0.7	18.6		0.1	3.2			0.2
Montipora patula	0.1	0.2	0.4			2.5			1.2		0.3	0.6		0.2	0.8		0.7	4.0
Montipora capitata	0.1	0.2		0.1	0.5	2.3		0.2	0.5		0.4		0.1	0.2	0.9		1.7	3.6
Pavona varians	0.1					2.2	0.1	0.3	0.5					0.5	1.7		0.2	0.3
Leptastrea purpurea	0.1												0.1					
Cyphastrea ocellina														0.1				
Transect total	17.6	7.4	66.9	61.6	38.8	93.1	76.1	76.8	93.9	5.4	28.8	56.5	44.2	73.4	92.2	72.5	92.3	95.8
SE	3.6	1.5	3.1	9.2	8.9	1.7	7.8	8.0	1.1	6.4	3.5	4.6	8.4	10.2	2.0	2.3	1.9	1.0
Species number	6	4	3	4	4	6	3	5	6	2	4	3	5	7	6	2	5	6
Species diversity	1.01	0.76	0.71	0.96	0.27	1.03	0.58	0.65	0.82	0.58	0.24	0.69	0.89	0.56	0.83	0.60	0.82	0.99

Species	T-5-6			T-5-10			T-5-20			T-6-6			T-6-10			T-6-20		
	1983	1993	2002	1983	1993	2002	1983	1993	2002	1983	1993	2002	1983	1993	2002	1983	1993	2002
Porites lobata	16.9	18.2	34.8	36.2	31.4	61.3	51.0	48.2	35.2		40.1	16.9		15.8	62.8		37.2	27.0
Porites compressa	0.1			12.5		2.0	19.0	13.1	51.3					2.2	3.5		34.6	66.0
Pocillopora meandrina		0.8	15.2	0.2	2.3	8.8	0.3	0.8	2.9		1.3	32.9		0.4	13.5		0.2	0.6
Pocillopora eydouxi															0.8			
Montipora patula		0.3	1.0		0.4	0.9		0.4	2.4		0.3			0.1	2.6			1.9
Montipora capitata		0.1	0.7	0.1	1.0	0.7	0.1	0.8	3.4		0.1			0.4	2.3			0.8
Montipora flabellata															0.6			
Pavona varians		0.5			0.1			0.4	0.7									1.9
Pavona duerdeni														0.1				
Leptastrea purpurea				0.1	0.1						0.5							
Palythoa tuberculosa											0.1							
Cyphastrea ocellina		0.1																
Transect total	17.0	20.0	51.7	49.1	35.3	73.7	70.4	63.7	95.9	0.0	42.4	49.8	0.0	19.0	86.1	0.0	72.0	98.2
SE	4.6	1.8	4.2	6.8	5.0	5.4		6.7	1.1		3.3	4.1		2.1	4.0		8.0	0.5
Species number	0.036	6	4	5	6	5	4	6	6		5	2		6	6		3	6
Species diversity	1.73	0.42	0.76	0.62	0.47	0.60	0.62	0.71	1.05		1.08	0.64		0.61	0.3		0.71	0.85

nearly vertical basalt cliff drops to a deeper reef platform at a depth of 8–10 m. The reef platform then slopes gradually to the limit of coral growth (~25 m) and terminates in a sandy plain. The zonation of coral community structure is typical of West Hawai‘i (Dollar 1982). The shallow zone is dominated by the pioneering species *Pocillopora meandrina* (Figure 4*E*), the mid-depth zone is dominated by various growth forms of *Porites lobata* (Figure 4*F*), and the deep zone is covered with a mixture of *P. lobata* and interconnected colonies of *Porites compressa* (Figure 4*G*).

Replicate surveys at six sites fronting the Mauna Lani Resort showed increases in mean coral cover on all 18 transects between 1983 and 2002 (Table 4, Figure 5). Increases were significant ($P = 0.02$) on 11 of the 18 transects between 1993 and 2002 (individual quadrat data were not available for the 1983 survey) (Table 2). There were no significant decreases in coral cover on any transect. Overall, increases in coral cover were greatest on the 6-m and 10-m deep transects. Mean coral cover was highest on the 20-m-deep transects, ranging from 92 to 98% of bottom cover at all six sites in 2002 (Table 4). Of the three surveys, coral cover diversity ($H'c$) was highest in 2002 on 10 of the 18 transects and highest in 1983 on the other eight transects (Table 4). Four transects, all of which were at depths of 20 m (T-1-20, T-3-20, T-4-20, T-5-20), displayed a sequential increase in diversity over the three sampling periods. Two transects, both in the shallow 6-m depth zone (T-3-6, T-6-6), had progressively decreasing diversity with time (Table 4).

The ranked abundance of pooled coral cover showed a consistent pattern of dominance on all three surveys. *Porites lobata* was the most dominant coral, followed by *Porites compressa*, with *Pocillopora meandrina* ranked third (Table 3). Together, these three species composed 95% (1983), 97% (1993), and 92% (2002) of coral cover. Compared with Honolua Bay, species of *Montipora* were far less abundant on the Mauna Lani transects, with a total pooled coral cover of about 1% in 1983, 2% in 1993, and 7% in 2003 (Table 3).

Coral community structure at site T-6, located off Puakō, was consistent with that at the other sampling stations. Mean total cover was 49, 86, and 98% at the 6, 10, and 20-m transects, respectively. Mean coral cover increased at all three depths between 1993 and 2002, with significant increases on the 10- and 20-m transects (Table 2). These results indicate that there was no measurable negative effect to the coral community from cesspools and septic systems along the shoreline during the study period.

Princeville

The Princeville Resort is located on the northern coastline of the island of Kaua‘i, which is the northernmost island of the main Hawaiian Islands (Figure 1, inset). The first phase of the resort included a hotel and golf course and was completed in 1971. As part of the environmental planning documentation for a second golf course, a study was conducted in 1980 to compare the condition of reefs off the existing golf course with control areas. This was done to evaluate potential impacts from the existing resort (R.W.G., unpubl. data). An identical study was repeated in 1995 for a projected new phase of resort development. And finally, a third investigation was conducted in June 2002 as part of this study.

The oceanographic setting of Princeville is strikingly different from the other two sites described in this paper. The reefs there are directly exposed to long-period open-ocean swells generated from winter storms in the North Pacific. Reef development is therefore restricted to species assemblages that are tolerant concussive forces of waves as well as sediment scour and abrasion that occurs during high surf events every winter.

The nearshore physiography off most of Princeville consists of a wide (up to several hundred meters), shallow (1–2 m) reef flat that was formed during the Holocene over the last 7000 yr (Easton and Olson 1976). The reef flat is covered with sand and rubble and is bisected by numerous sand-filled channels perpendicular to the shoreline. There are also submerged streambeds from several existing streams that flow to the shoreline. Coral cover on the reef flat is sparse, with

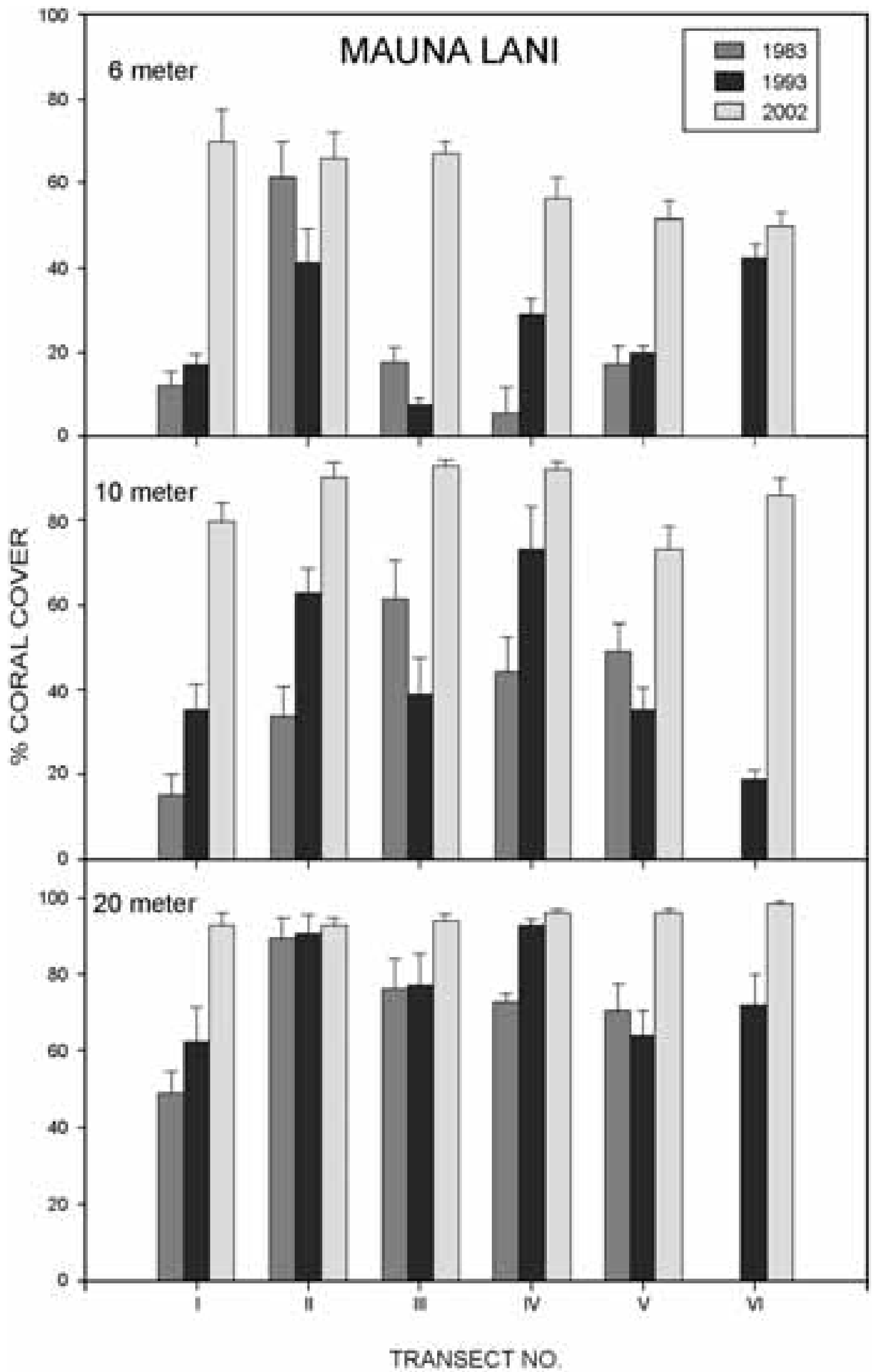

Figure 5. Histogram showing total mean coral cover (+SE) from benthic transect surveys off the Mauna Lani Resort in 1983, 1993, and 2002.

living colonies composing no more than about 2% of bottom cover. The seaward edge of the reef flat terminates in a narrow reef crest that is partially subaerial at low tide and absorbs much of the force of breaking waves. Seaward of the reef crest, the outer reef zone consists of spurs and grooves that extend to a depth of approximately 8–10 m. Between the spurs and grooves, the bottom topography is relatively flat and slopes gradually into deeper water. Coral growth reaches a maximum at a depth of about 12 m.

TABLE 5

Percentage Cover, Number of Species, and Species Cover Diversity (*H′c*) for Phototransects Conducted in 1980, 1995, and 2002 off the Princeville Resort, Kaua'i, Hawai'i

	Transect								
	T-1			T-2			T-3		
Species	1980	1995	2002	1980	1995	2002	1980	1995	2002
Porites lobata	5.7	4.6	10.3	5.3	2.7	9.0		1.8	0.2
Porites compressa	0.7	1.7	1.2	1.5	1.0	3.7			
Porites brighami							0.3		0.1
Pocillopora meandrina	0.3	0.5	1.5	0.04	1.6	2.2	2.0	1.7	5.4
Pocillopora damicornis		0.6							
Montipora capitata	2.2	5.0	5.1	0.6	4.4	10.8	0.5	0.6	
Montipora patula	1.8	6.4	14.3	6.4	6.7	16.2	2.9	9.5	5.2
Montipora flabellata	5.1	4.8	4.5	0.7	3.8	2.6	1.1	0.4	10.3
Pavona varians							3.5	2.1	2.9
Pavona duerdeni	0.4	1.1	1.2	0.5	0.4	2.3	0.8	0.6	2.1
Psammocora stellata		0.7			0.6				
Cyphastrea ocellina		0.5							
Palythoa tuberculosa	0.2						0.5	1.6	8.5
Fungia scutaria		0.1					0.1		
Transect total	16.4	26.0	38.1	15.0	21.2	46.8	11.7	18.3	34.7
SE	2.0	2.0	5.3	1.6	1.8	4.7	1.8	1.6	3.5
Species number	8	11	7	7	8	7	9	8	8
Species diversity	1.63	2.02	1.59	1.35	1.78	1.68	1.71	1.56	1.70

	Transect								
	T-4			T-5			T-6		
Species	1980	1995	2002	1980	1995	2002	1980	1995	2002
Porites lobata	10.9	4.1	3.0	16.2	21.3	18.1	3.2		6.7
Porites compressa	0.8		2.3	3.6	0.3	2.0	2.9		2.1
Pocillopora meandrina	1.1	4.6	0.8	0.9	5.1	2.1	0.2		0.7
Pocillopora eydouxi									1.4
Montipora capitata	0.2	1.4	6.3	0.6	0.4	0.3	1.7		0.7
Montipora patula	6.4	13.4	7.7	4.0	5.7	17.7	3.8		22.4
Montipora flabellata	0.4	1.5	10.6	0.1	1.7	4.8	0.1		0.3
Pavona varians		0.2			0.1				
Pavona duerdeni	0.4	0.7	0.6	0.6	0.9	0.4			
Fungia scutaria			0.1						
Porites (S.) canvexa						0.2			
Palythoa tuberculosa		0.1	0.1	0.2	0.4	0.3	0.2		
Transect total	20.2	26.0	31.5	26.2	35.9	45.9	12.1		34.3
SE	2.1	2.1	3.8	1.9	4.3	3.2	1.4		4.6
Species number	7	8	9	7	9	9	7		7
Species diversity	1.17	1.42	1.65	1.23	1.27	1.31	1.51		1.10

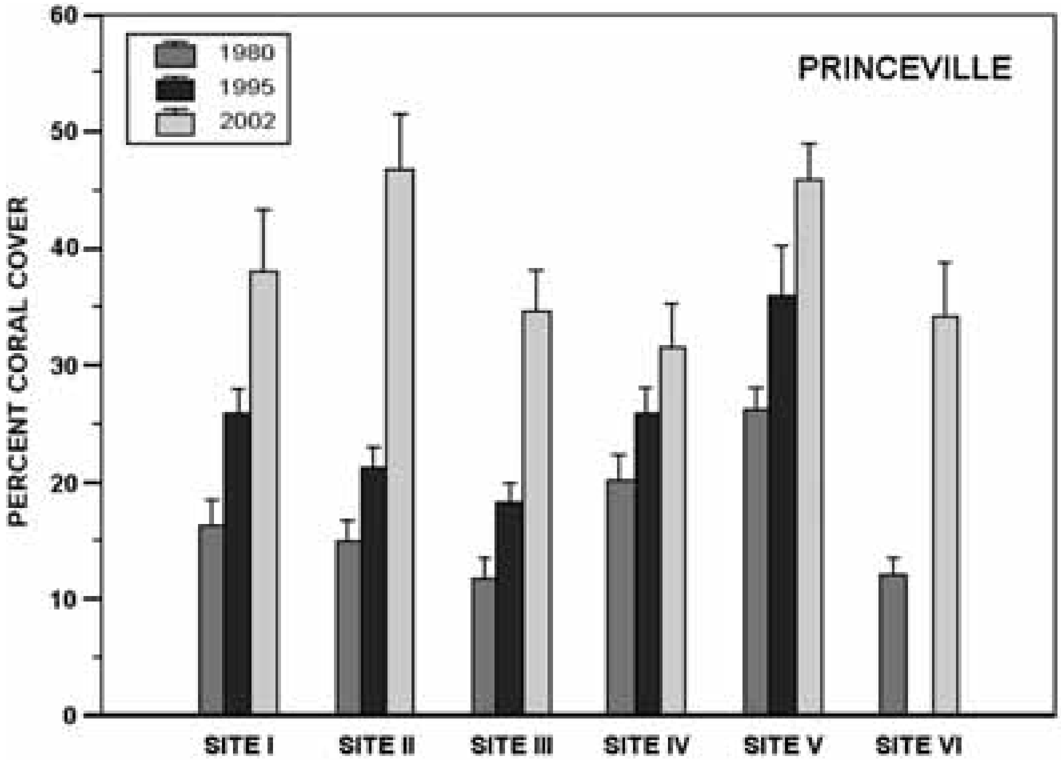

FIGURE 6. Histogram showing total mean coral cover (+SE) from benthic transect surveys off the Princeville Resort in 1980, 1995, and 2002.

Total mean coral cover increased on all transects on each succeeding survey (Table 5, Figure 6). Between 1980 and 1995 the increases in coral cover were significant on two of the five transects. Between 1980 and 2002 the increases were significant on all six transects (Table 2). Coral cover diversity showed no consistent pattern of change over the three surveys (Table 5).

Ranking pooled coral cover showed *Porites lobata* to be the dominant species in 1980 and 1995. However, *Montipora patula* was the most abundant coral in 2002 (Table 3). Both of these species occur primarily as flat encrustations on the limestone platform (Figure 4*H*). *Porites compressa*, which was a major component of the coral assemblages at Honolua Bay and Mauna Lani, was relatively scarce at Princeville, composing less than 10% of coral cover during all three surveys (Table 3).

DISCUSSION

The time-series data indicate very different results from the two sites located on open coastlines compared with the site located in an enclosed embayment. The case history for the embayment site is discussed first.

Coral cover in Honolua Bay was reduced substantially between 1992 and 2002, primarily as a result of smothering by sediment runoff. Because there were no surveys between 1992 and 2002, it is not certain if coral cover was reduced exclusively by the most recent rainfall/runoff event. However, if the reduction in coral occurred as a result of the early 2002 storm, it is of interest to evaluate the magnitude of this event in the context of

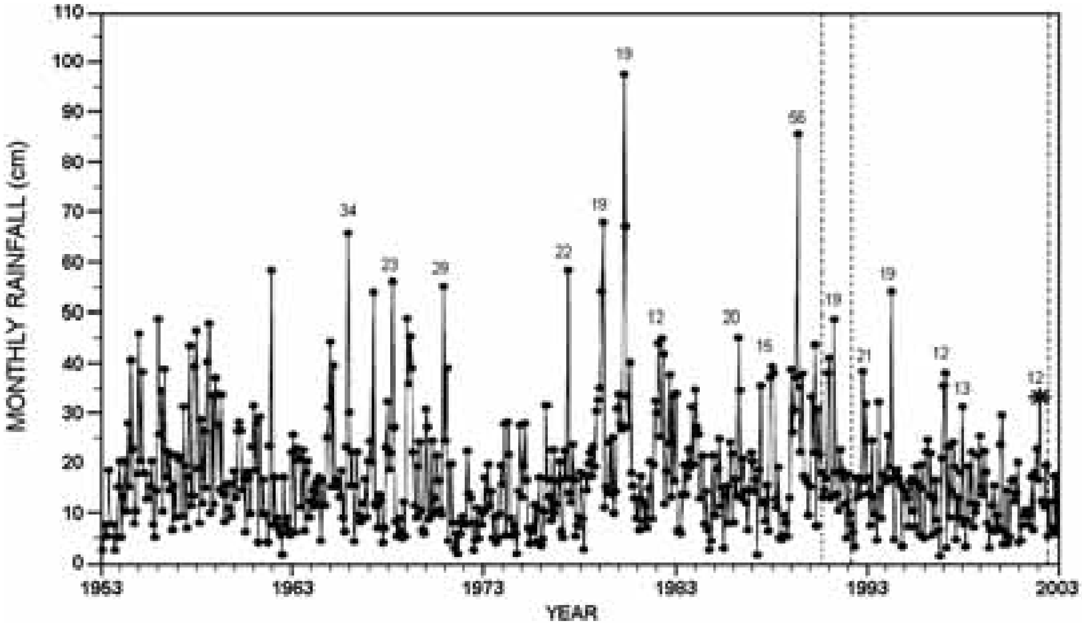

FIGURE 7. Total monthly rainfall recorded from a gauge in Maui Pineapple Co. field 45 directly above Honolua Bay from 1953 to 2002. Number above peak rainfall months is highest 24-hr accumulation in that month. Asterisk (*) indicates storm event in January 2002 that preceded benthic survey in summer 2002. Dashed lines indicate time of benthic surveys in 1990, 1992, and 2002.

all three coral surveys. Based on the sediment remaining in the bay 6 months after the early 2002 storm, as well as the level of coral mortality, one would expect that the 2002 storm was of unusually high magnitude. However, the total monthly rainfall and peak 24-hr accumulation in the highest-elevation rain gauge that drains into the Honolua Stream was not unusually high for the January 2002 storm relative to other rainfall events from 1953 to 2002 (Figure 7). Total rainfall for January 2002 was 33.5 cm, with a peak 24-hr accumulation of 12 cm. Between 1953 and 2002 there have been 55 months with total rainfall greater than 35 cm and 5 months with total rainfall greater than 60 cm. Of these peak events, at least 14 had daily accumulations greater than occurred in January 2002 (Figure 7). Both the 1990 and 1992 surveys, which reported substantially higher coral cover than the 2002 survey, occurred only 1–2 yr after storms of higher total and 24-hr rainfall than recorded in 2002 (Figure 7).

Retention of sediment within the inner bay thick enough to cause smothering of corals is also a function of wave-driven circulation and flushing of the embayment. Long-period swells from the north during winter months produce high surf at the northern headland of Honolua Bay (Figure 1). Although most of the energy of breaking waves is dissipated before reaching the inner bay, circulation is clearly increased during periods of large surf. Records of north swells classed by number of days per month of breaking surf between 3.5 and 5 m and greater than 5 m suggest a slight trend of decreasing frequency of large surf since about 1985 (Figure 8). There was no indication, however, of insufficient north-swell wave action to flush sediment from Honolua Bay in 2002 relative to other years.

A second factor that can affect circulation in Honolua Bay is short-period waves generated by strong south-southwesterly ("Kona") winds. These events are generated by local weather and occur for short periods

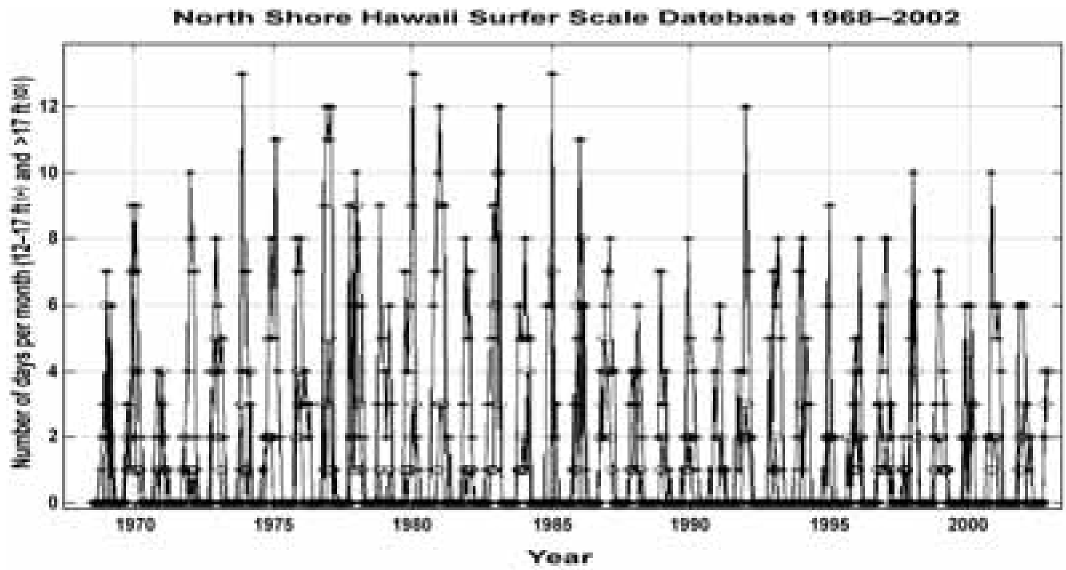

FIGURE 8. Number of days per month of surf between 3.5 and 5 (*) m and greater than 5 m (0) reported on the north shore of O'ahu from 1968 to 2002.

primarily during the winter months. Funneling through the channel between the islands of Moloka'i and Lāna'i strengthens the intensity of Kona winds affecting Honolua Bay. Short-period waves generated by Kona winds are generally smaller in size than long-period swells from the north, but the angle of approach directly into the mouth of Honolua Bay may result in more resuspension of sediment in shallow water. A histogram of wind velocity shows that the frequency of south-southwest wind is highly variable (Figure 9). It also suggests that the period following the January 2002 storm was a period of moderate Kona winds. In fact, south-southwest winds were more prevalent during the remainder of the winter of 2002 than following two other winter storms in 1989 and 1991 that did not produce a large effect on coral community structure (Figure 9).

Comparing the time-series records of coral cover, rainfall, wave activity, and wind exposure (short-period waves) indicates that the reduction in coral cover within Honolua Bay in 2002 was not the result of a single causal factor. The 2002 rainfall event was not an unusually large storm, nor was wave activity (causing resuspension of sediment) anomalous in months following the storm. Land-use practices, in terms of pineapple agriculture, were not different than during other years (W. Nohara, pers. comm.). If storm intensity (in terms of total rainfall) is the sole factor equated with coral mortality, it is likely that there would be few remaining live corals in Honolua Bay, because there have been many intense storms in the last 50 yr. Thus, it is clear that total rainfall and runoff per se is not the only factor causing coral mortality. Rainfall records do not differentiate intensity of rainfall within a 24-hr period, which may be the most critical factor in determining the magnitude of sediment discharge from land to the bay. For example, even with the numerous sediment-retention devices that have been built in the Honolua watershed since 1996, the 2002 rainfall/runoff event may have been so intense as to overwhelm the capacity of these structures, resulting in substantial discharge of sediment to the embayment. Had the same overall rainfall occurred over a longer duration, sediment input to the bay may have been much less.

It is also important to note that coral as-

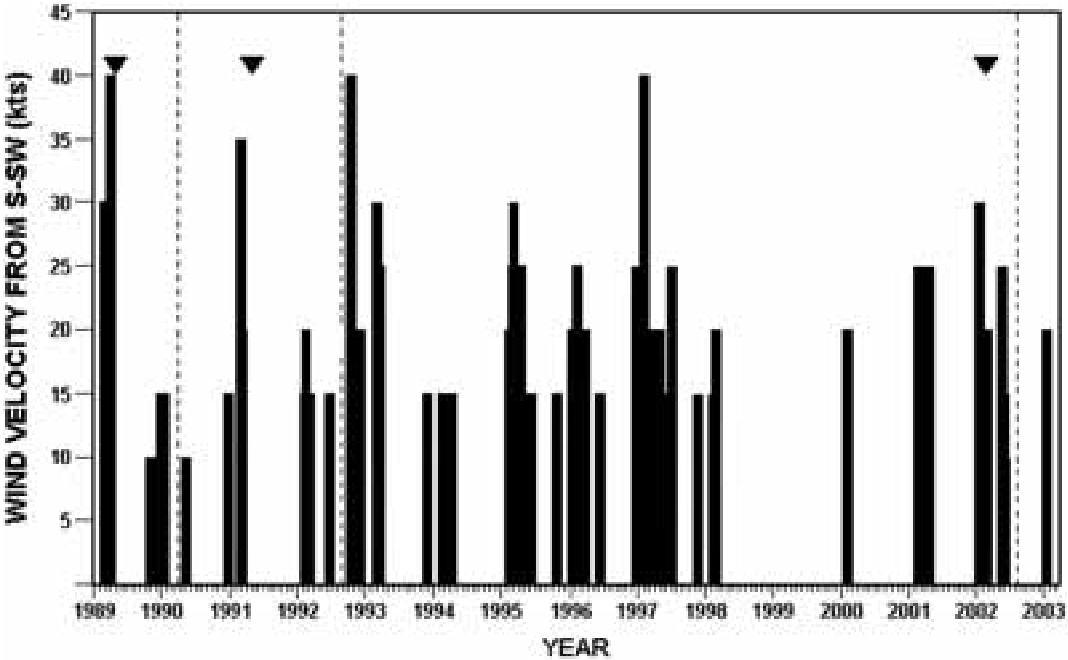

FIGURE 9. Kona (south to southwest) wind velocity from 1989 to 2002 reported on O'ahu. Dashed lines indicate time when benthic surveys were conducted in Honolua Bay. Inverted triangles indicate peak rainfall events in April 1989, April 1991, and January 2002.

semblages in the inner bay are dominated by sediment-resistant species, indicating that episodic sediment inputs have been frequent in the recent oceanographic history of the bay. We suggest that the decline in coral cover measured in 2002 is part of a cycle of impact and recovery that has occurred in the bay many times in the last 50 yr. Such a cycle fits within the successional model known as the "intermediate disturbance hypothesis" (Grigg and Maragos 1974, Connell 1978, Grigg 1983). In this model, high diversity is maintained by disturbance operating at intermediate levels that is sufficient to prevent resource monopolization, thus maintaining communities at "preclimax" successional stages. Occasional severe and intense disturbances may destroy a community completely and reset the successional process back to time zero.

In open coastal locales, the major source of disturbance is stress from waves (Dollar 1982, Grigg 1983). In Honolua Bay, which is partially enclosed and sheltered from waves, the major source of disturbance is sediment input and retention. Intermediate levels of sediment input after storms coupled with moderately long residence time within the bay may be sufficient to reduce the dominance of coral genera that usually dominate calm-water habitats (e.g., *Porites compressa*) in favor of more sediment-resistant species (e.g., *Montipora* spp.). Periodic events that result in substantial sediment input coupled with prolonged retention in the inner embayment may result in mortality of all species that are buried. Subsequent flushing of the sediment exposes bared substratum suitable for settlement by new recruits. Thus, the coral communities in the inner portions of Honolua Bay may result largely from the interaction between disturbance and recovery time. In this case the disturbance is sediment input rather than wave stress. The high coral cover in the inner bay during the 1990 and 1992 surveys, particularly by sediment-resistant species, shows that sediment stress is not continuous, nor is it completely limiting to coral growth. If there were not such a cycle of recruitment and regrowth, no living coral would exist in the inner bay. Future studies might differentiate between episodes of sediment runoff that result in impact versus those that do not. Another investigation that would be of interest in understanding the effect of land use on coral community structure would be to core the reef in the inner bay to determine if there were changes in species assemblages coinciding with the introduction of agriculture.

Contrary to conditions at Honolua Bay, coral communities off the Mauna Lani and Princeville Resorts appear to be natural assemblages, with no measurable impact from anthropogenic activities related to either resort or private residential development. Off Mauna Lani, vast tracts of undisturbed *Porites compressa* indicate that destructive wave events have not been sufficient to disrupt the successional process over the last two decades. The lack of wave disturbance, along with no other impacts such as sediment or nutrient input, has allowed the community to attain a near-climax stage of coral reef development with nearly all available substratum colonized. At Princeville, which is subjected to annual wave stresses far greater than at Mauna Lani, community development has remained at an intermediate successional stage with lower cover and higher diversity. It may even be possible that resort development there is contributing to an increase in coral coverage by mitigating surface runoff. Alternatively, sediment impacts on offshore reefs may always have been minor, because most of the sediment carried to the ocean by streams is deposited on the reef flat or rapidly dispersed by wave action. It is also possible that the increased coral cover off Princeville is a response to the slight decrease in frequency of large surf from winter swells since 1985 (Figure 8). At both open coastal sites, continuous increases in coral cover during the last two decades indicate that anthropogenic activities on land have not significantly affected coral community structure.

CONCLUSIONS

Concern over the condition of coral reefs globally has increased substantially over the last decade. Many coral reef communities have deteriorated from human impacts such as overfishing, destructive fishing techniques, sedimentation from poor land management, mining and dredging activities, oil and industrial pollution, and eutrophication. Although geographically widespread, many of these problems are often localized, primarily near centers of human population in Southeast Asia and the Caribbean. Destructive fishing practices are in fact far-reaching and some are increasing in intensity. Nevertheless, it is important to place this recent history in a larger evolutionary context. Over geologic time coral reefs have displayed an impressive resilience in the face of natural stressors such as hurricanes (typhoons), extratropical storms, intense long-period waves, tsunamis, crown-of-thorns starfish outbreaks, infestations of disease, climatic change, species shifts, and sea-level change (Brown and Howard 1985, Grigg and Dollar 1990, Buddemeier 1992, Smith and Buddemeier 1992, Grigg 2000). Because coral reefs have been robust, persistent, and resilient over geologic time on a global scale, it is important to weigh the inputs of anthropogenic change against this long history.

It has been well documented that the accretion, growth, and community structure of most coral reefs in the Hawaiian Islands are primarily under the control of wave forces (Grigg and Maragos 1974, Dollar 1982, Grigg 1983, Dollar and Tribble 1993, Grigg 1998). Off open coastlines, the community structure of coral reefs in Hawai'i appears to be largely a function of the interaction between disturbance and recovery time. Community succession is continuously interrupted by intermediate-level wave events, which prevent resource monopolization and maintain high diversity. Infrequent high-intensity events can and do disrupt the entire community and set the successional process back to time zero (Grigg 1983). In wave-sheltered areas, a variety of other factors, including but not limited to sedimentation, eutrophication, algal overgrowth, temperature, light, and salinity, can and do replace wave stress as the principal stress regulating community composition and succession.

Studies of succession have shown that anthropogenic impacts on coral reefs in Hawai'i are superimposed on these naturally controlling forces (Grigg 1994). In general, anthropogenic impacts dominate in environments where wave forces are not the major controlling factor. These environments typically are embayments and lagoons that are protected from wave stress, resulting in relatively long residence time of the overlying water. The data from the three case studies reported in this paper indicate that at the open coastal sites, coral abundance has increased over the last several decades in the presence of extensive shoreline resort development. Coral communities off the Mauna Lani Resort on the island of Hawai'i are thriving, with little or no apparent effect of land-based anthropogenic activity. Vast tracts of undisturbed *Porites compressa* indicate that destructive wave events have not occurred there for over two decades. The lack of destructive storm-wave disturbance, along with lack of changes associated with land use, has produced a near-climax community with nearly all available substratum colonized. At Princeville, there has also been a continuous increase in coral cover during the last two decades.

On the other hand, anthropogenic impacts can be serious in localized areas where water circulation is restricted. In semi-enclosed Honolua Bay, where a lack of wave-induced circulation limits resuspension and water exchange, sediment input has exerted a significant effect on coral community structure. Large-scale pineapple agriculture requires land with periodically exposed soil in a climate that produces occasional heavy rains. Sediment input into the bay occurred long before human activity, but it undoubtedly has changed with changing land use. The coral assemblages that are currently present reflect such input, with abundant coverage of species that are sediment-resistant. It is likely that the recent decline in coral cover in Honolua Bay is part of an ongoing cycle of impact and recovery that has occurred for at least the past 50 yr. The extent of damage to corals appears to have been a function of the combined effect of rainfall intensity, sediment runoff, and wave resuspension and flushing.

The time-series data sets described in this paper provide empirical evidence that effective coral reef management should be based on case-specific and objective scientific data. Currently there is a strong consensus that coral reefs are threatened on a global scale by the activities of humans. Although such alarm is well justified for many reefs of the world, this view is not an accurate description of most Hawaiian coral reefs. Our results indicate that wave exposure and water circulation far overshadow the effects of shoreline development on open coastlines. Sediment from anthropogenic sources may enter the ocean along open coastal areas, but the impacts are likely to be minimal or ephemeral owing to resuspension and removal by wave action. Major anthropogenic impacts on Hawaiian coral reefs owing to land-derived stresses are generally restricted to areas where ocean circulation is confined. Management concerns should concentrate on those specific areas where circulation is confined and sediment retention is likely (e.g., embayments). It is important to note that these conclusions do not apply to anthropogenic activities such as overfishing and alien species, which are not directly related to activities on land. In particular, the ecology of alien species may not conform to general patterns that control coral reef community structure, and therefore their patterns of distribution and abundance may represent exceptions to the general scheme.

These conclusions do not mean that major efforts to manage coral reefs in Hawai'i are not seriously needed. Rather, management effort should be focused on areas where it can produce the most benefit (e.g., embayments). Overall this strategy should strengthen the efficiency and effectiveness of coral reef conservation. Even though embayments comprise less than 10% of the coastal area of Hawai'i, our results indicate that these areas are where the major management effort should be focused. It is also important to recognize that the embayments are major sites for recreation, fishing, and numerous boating and even commercial activities. In contrast, coral reefs off open wave-exposed coastlines in Hawai'i are generally quite healthy and are likely to remain so, even though succession may be frequently disturbed by high-wave events. The future condition of these reefs will more likely be a function of response to natural forces.

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